Reference Document 6

# Proposals from Visionary Council

(Domains in the Moonshot Research and Development Program which should be addressed with priority)

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Domains in the Moonshot Research and Development Program which should be addressed with priority

Hiroaki Kitano

| Issues to be addressed with priority (Challenge / Big Goal) |
|---|
| **Automation of scientific discovery** |
| General idea |
| Japan's future depends on how we could carry out scientific discoveries and technological breakthroughs to bring industrial and social reforms swiftly. When we think about the future of humanity, we find ourselves facing loads of problems such as climate change, resource depletion, aging society and medical issues. It is clear, however, that scientific discoveries and technological breakthroughs play a huge role in overcoming these challenges. It is true that we cannot settle issues we face with science and technology alone. It is also true, however, that we cannot solve such problems without using science or technology.<br><br>Following the principle that the most disruptive innovation undermines contemporary, mainstream systems and concepts, I propose that we aim to automate scientific research itself, redefine science, and ultimately build a system which mass produces scientific discoveries that are extremely unique and advanced.<br><br>At the same time, the endeavor for automated scientific discovery will shed some light from science on the fundamental question: What is the essence of scientific discovery?<br><br>What comes after "He who rules the data rules the world" is the era of "He who rules scientific discovery rules the world," and there is no doubt that this field will be the most important R&D field. It should be the most likely candidate of the Moonshot Research and Development Program. |
| We appreciate if you could provide any idea on Moonshot targets (Missions). (Optional) |
| **"Develop an AI system which autonomously makes Nobel-Prize-worthy discoveries by 2050"** |
| We appreciate if you could elaborate on the above. (Optional) |
| I. Setting targets<br><br>Moonshot targets need to be clear and easy to understand for anybody. If we put it simply as "AI which makes scientific discoveries," it does not convey a clear image of what level of discoveries we are aiming for, hence, will not serve as a target. By expressing it as "Nobel-Prize-worthy discoveries," we can make it clear that we are aiming for an extremely challenging target. As well, by adding the condition "autonomously," we can make this target more challenging as it would not be attainable just by building a system for data analysis or precise machine learning. By articulating the deadline "by 2050," we can make it clearer how to set milestones along the way during the research.<br><br>Winning the Nobel Prize in Physiology or Medicine will have a huge impact, so the relevant fields of study are recommended. However, there is no problem in conducting projects in physics or chemistry at the same time. |

As well, we can set up a Nobel Turing Challenge in which we aim for the Prize without being found out that the actual discoverer is AI. It would be the highest level of a Turing test.

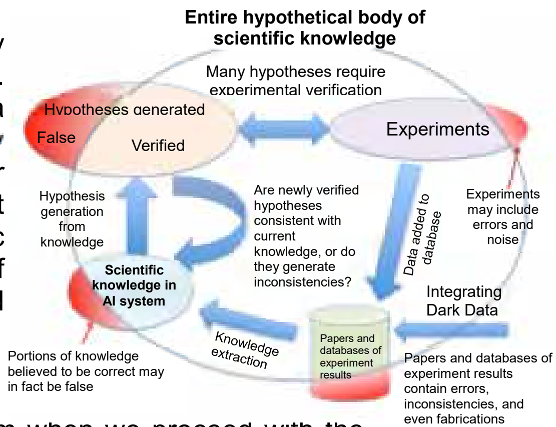
II. Recognizing the current state. “The process of scientific discovery remains the same as that in the pre-industrial era.”


Thanks to the accelerated development, there are devices which create large volume of measurement data while analysis methods have rapidly advanced too. Meanwhile, we have made no progress in the essential process of scientific discovery, still relying on thinking skills of individual researchers, their scientific intuition, and serendipity. Far from making progress, we even face difficulties in dealing with mass data these days.

Systems biology has been around 20 years. Meanwhile, system-theory-based research has advanced and contributed to the dramatic progress of multidimensional, comprehensive, quantitative measurement technology. However, the current research is unable to harness all these advances. I believe this is because it is highly difficult for us, humans, to understand complex phenomena and data which reflect them with our information processing capability and cognitive capacity.

Subjects we try to understand and control are so complicated that we cannot expect to understand them without somehow breaking through limitations of our cognition capacity. Through the industrial revolution, we obtained an “engine,” or driving power. Likewise, the Moonshot Challenge is a challenge of obtaining an “engine for scientific discovery” and <u>a challenge of overcoming our cognitive limitations.</u>

III. Working hypothesis for achieving the target “Scientific discovery is made by unfolding and exploring huge hypothesis space.”




The process of scientific discovery basically consists of presenting and verifying hypotheses. The basic process is universal, in which a hypothesis is presented, whether it is generated by the researcher’s inspiration or lucky mistake, or logically, and it is verified. If we promote the project by sticking to this principle, automation of scientific discoveries will be automation of exploration of hypothesis space (in fact huge space) and verification.

Based on this hypothesis, first we need to develop a cycle as illustrated by the right diagram when we proceed with the project. At each step of the process, specific questions to be answered can be defined individually.

This approach, however, is likely to invite counterarguments, e.g., “Major discoveries are made where they are not expected. Can the approach in question lead to discoveries that are beyond expectations?” “The approach is unrealistic because space to be explored is too huge.” These voices happen to be the same as what we heard when researchers were taking on a challenge of beating humans in chess and Shogi with computers. However, the history of AI research has demonstrated that it is possible to build AI which surpasses human capabilities by brute force, that is, comprehensive exploration and learning from solution space. Scientific discovery would require research and technological development which correspond to the size of exploration space that is tremendously huge and much greater than solution space of chess or shogi but the basic principle will be the same.

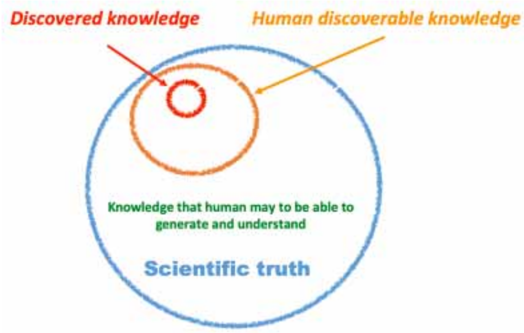
At the same time, there are loads of phenomena which we believe we can account for somehow but have not actually generated or verified hypotheses for. It is extremely important to apply automatic hypothesis generation and verification to these phenomena and reinforce our knowledge base, through which we may make huge discoveries. In this respect, the argument that huge discoveries can only be made where they are not expected may be based on the cognitive bias.

A series of papers provide discussion on limitations of the current process of scientific discovery and approaches for achieving targets.[1]

IV. What does achieving the target mean? "Fountain of knowledge" and "Discovery beyond human knowledge"

It is important to understand what achieving this target means.

First, we will see knowledge discovered day and night and accumulate in abundance. Newly found knowledge probably includes that which could lead to new therapy or new material. By running this knowledge discovery process 24/7, the developer of the process may obtain knowledge and technology in almost all fields in an exclusive manner in addition to AI technology. It has an exceptionally huge impact on industry and society, an impact that is incomparable with data monopoly.



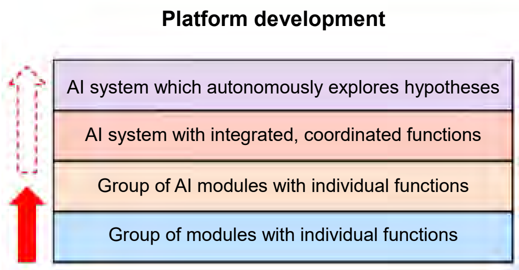

In addition, it will bring about a scientific paradigm shift. Scientific knowledge we have discovered so far is limited to subjects and laws we can express and recognize. However, if we can run a cycle in which an AI-based system discovers even ways to express hypotheses, generates hypotheses and verifies them, we may obtain scientific knowledge that we would not be able to otherwise. It is no surprise that such discoveries by AI cannot be understood by humans firsthand. Through approximation and simplification processes, they need to be converted to a form of knowledge that we can understand. There is no guarantee that all laws of nature exist the way we can understand.

However, by using AI which makes scientific discovery, we may be able to step into areas which would not accept humans otherwise, and that is likely to urge us to radically change our way to deal with and understand nature and the degree of our use of nature. Accordingly, it is clear that this challenge is one of the most critical challenges for science today.

[1] Kitano, H., "The Day AI Win the Nobel Prize and the Future of Humanity ─ An Ultimate Grand Challenge in AI and Scientific Discovery─," *Journal of the Japanese Society for Artificial Intelligence, Vol. 31, No. 2,* March 2016
Kitano, H., "Artificial Intelligence to Win Nobel Prize and Beyond ─ Creating the Engine for Scientific Discovery," *AI Magazine,* Spring 2016

V. What can be gained by the time of achieving the target "Acceleration of science by AI"

This challenge is unique in that it could lead to the creation of industry-transforming technology through acceleration of science in a series of steps in the course of target achievement. AI which makes scientific discovery does not consist of a single system. It first starts with application of automation and AI to many steps related to scientific discovery, e.g., database, data analysis automation, experiment planning, experiment automation, etc. Then a function to coordinate these steps will be added, which will realize a series of process from hypothesis generation to experiment verification. This process needs to be realized on a common platform.



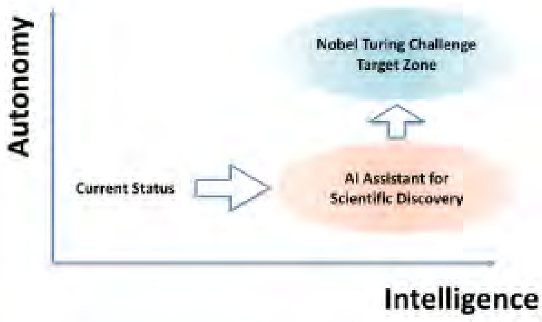

If the project is promoted by following this approach, individual modules can be upgraded successively, leading to commercialization and new business, which could accelerate science. As well, protocols and data will be shared at an accelerated pace, which will enable verification of experiment's reproducibility and put an end to data falsification from intrinsic motivation.

When this project starts to produce results, research institutions which have not introduced AI will lose their competitiveness. That will further accelerate the project.

VI. Is autonomous discovery possible? "Group of various unique AI vs. Universal single AI"

So far, I have not touched on how to set a question to solve. The most common form of introduction of AI to research would be researchers setting questions to solve and using AI systems to solve them. (AI Assistant: See the right diagram.) If realized, this would have an enormous impact too but if we take one step further, we can assume that AI can autonomously set questions to solve. That would shed some light on what interest humans.

If one's interest or awareness of issues is based on his or her individual experience, we can assume that AI systems can set questions based on a series of experiences. How to nurture curiosity in AI and how to make it explore information of its own volition are topics that researchers are actually working on although at a primitive level.




If one's interest or awareness of issues is conditioned by his or her experience, each AI will also be equipped with unique research history and information when it is developed, and a single AI system which has access to all information will not lead to a major discovery. Uneven distribution of knowledge and information will be a key factor. In this case, each AI system is likely to continue research the way human researchers do, so it would be impossible to distinguish AI and humans. It is also related to division of hypothesis space and may provide an answer to the question concerning exploration efficiency.

VII. Ultimate Moonshot target "Technology which changes the future of humanity"

This target is the ultimate Moonshot target. Scientific research is a foundation of the current human civilization. Making it autonomous or automated will drastically transform our civilization. As well, the first country or corporation which realizes AI which makes scientific discovery will establish overwhelming advantage over others in wide areas.

With engines as its source, the industrial revolution ushered in the eras of the coal/oil industry, auto industry, machine tools, and manufacturing industry. Through the information revolution triggered by data, the IT industry has changed industrial structure and social structure. The Moonshot Program aims for new scientific revolution, where automatic discoveries of knowledge will lead to solutions to global issues or simply to our greater understanding of the world.

At the same time, however, the scientific revolution will make new structure inevitable where a corporation which owns such technology, and thereby discovers and understands new knowledge will have huge influence on companies which use such knowledge. Technology created through this challenge will wield extremely powerful influence. Therefore, Japan should make an all-out effort to conquer this challenge and strive to realize and properly implement the technology with strong leadership.

A research system and individual milestones were omitted in this response sheet.

# Domains in the Moonshot Research and Development Program which should be addressed with priority

Yoshimitsu Kobayashi

| Issues to be addressed with priority (Challenge / Big Goal) |
|---|
| To maintain the sustainability and biodiversity of the earth by solving climate change and environmental issues, we should establish "Global Defense Corps" which brings together R&D functions for related technologies, functions of collecting and analyzing various data, functions of designing necessary systems and recommending policies in a comprehensive manner. (It should completely integrate arts and sciences and include virtual combination of these functions.) |
| General idea |
| To maintain the sustainability and biodiversity of the earth, we need to aim for the largest and quickest effect by combining the following efforts strategically. To this end, it makes sense to establish "Global Defense Corps" by consolidating various functions in one place.<br><br>(Examples of topics of "Global Defense Corps")<br><br>➢ Reduction of CO2 emissions, Carbon dioxide Capture/Utilization/Storage (CCUS), artificial photosynthesis<br>➢ Water-saving farming methods, increasing yield of agricultural, livestock and marine products by using biotechnology<br>➢ Space-based solar power, nuclear fusion, DC power transmission by superconductivity, high-performance storage batteries<br>➢ Accurate carbon-Life Cycle Analysis (c-LCA) and corporate information disclosure based on blockchain technology and carbon consumption tax in accordance with them<br>➢ Radical solution to the plastic waste issue<br>➢ Conservation of the diversity of ecosystems, species, and genes<br>➢ Exploration of socioeconomic systems for implementation of the above in society |
| We appreciate if you could provide any idea on Moonshot targets (Missions). (Optional) |
| Setting scientific and quantitative Moonshot targets (Missions) that are directly related to the solving of issues to be addressed with priority (Challenge / Big Goal) should be one of the missions of the "Global Defense Corps." |
| We appreciate if you could elaborate on the above. (Optional) |
| The reason for the above is because setting KPIs (or Missions) that are the most critical and effective and regularly measurable based on science will determine the effectiveness of the "Global Defense Corps." |

# Domains in the Moonshot Research and Development Program which should be addressed with priority

Naohiro Nishiguchi

| Issues to be addressed with priority (Challenge / Big Goal) |
| --- |
| No matter where people live in the world, when a disaster occurs, a rescue mission using the latest technology is completed, restoring living/business environment to the pre-disaster level within 15 minutes of the disaster occurrence. |
| **General idea** |
| • The above challenge is measurable in a concrete way.<br>• It is a target many think would be unattainable.<br>• It has appeal to many countries. |
| **We appreciate if you could provide any idea on Moonshot targets (Missions). (Optional)** |
| |
| **We appreciate if you could elaborate on the above. (Optional)** |
| |

# Focus areas for the Moonshot Research and Development Program

Taiyo Fujii

| Focus agendas (Challenges/Ultimate goals) |
|---|
| This Program should cover three areas: technological/engineering goals, solutions for environmental agendas, and resolution of social issues.<br>First of all, development projects that are feasible from technological or engineering aspects but have yet to be implemented should be made into this Program's flagship initiatives by giving them seed money.<br>At the same time, undertakings for solving environmental/social issues need to be subsidized.<br>For the latter challenges, sufficient funds should be allocated for basic studies in social science and humanities, with milestones set to perform empirical experiments with local governments and adopting successful programs into national framework. |
| Description |
| The technological/engineering development projects, e.g. large-scale initiatives such as space elevator, extending railroads into continental networks, or complete mapping of genome protein, should be driven by an assembly of third parties inside/outside Japan, a money/patent pool, and deregulation in relevant areas.<br>In the environment area, existing initiatives by various groups should be combined to set a tangible goal for this challenge, e.g. "creation of a carbon exchange market handling 50 trillion USD transactions every year."<br>For resolving social agenda, results of pilot projects in select prefectures and municipalities can be expected to lead the way to more women participating in society/politics and help determine the schedule and approach for introducing universal basic income, as the first step to building a safe society.<br>The mission of Moonshot Research and Development Program is to establish a new role model for Japan's society. It cannot afford to look over the nation's existing problems. For example, the lack of suitable employment for aspiring academics after completing graduate courses- a result of the failed graduate school policy – needs to be addressed by hiring them as research staff members or offering alternative options thorough this Project. At the same time, the percentage of women in this Project must be regularly updated to the steering committee, while designing the entire scheme with the aim of female members constituting 30 percent of managerial as well as staff positions. These approaches will vitalize Japan regardless of individual challenges' success. |
| Moonshot Goal (Mission) ideas, if any (optional) |
| 100 local governments participating in a pilot project for universal basic income (UBI) to prove its feasibility and create a roadmap for the society in the 21st century. |
| Description of the above ideas (optional) |
| Japan should be the pioneer in accepting the UBI as a new basic human right.<br>The UBI, partially introduced now as child benefits and other forms of financial assistance for the needy, should be extended to workers and senior citizens as an alternative for pension and other existing social welfare systems. This can solve many social problems. By giving assurance that unemployed people would not starve, the worker redundancy regulations burdening so many Japanese businesses can be eliminated, while wages will automatically rise. On the other hand, it may lead to a smaller workforce and many other new issues. To validate these expectations, prefectures and municipalities across Japan, large and small, need to join a pilot initiative to assess the impact of UBI. This experiment, the first of its kind in the world, can help Japan build a "future" that Nordic countries were once thought to have. |

Ideas around the government's primary balance must also change. Offering funds to organizations researching the modern monetary theory (MMT), discussions with the Bank of Japan, and sending messages through international UBI conferences are all requisite steps.

Supplementary material from Mr. Kitano



Article

# The Day AI Wins the Nobel Prize and the Future of Humanity

## - An Ultimate Grand Challenge in AI and Scientific Discovery -

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Keywords: systems biology, scientific discovery, grand challenge

## 1. Introduction

What is the most important thing that AI can achieve? There can be many answers. If an AI system can make a major scientific discovery by boosting scientific knowledge, that would be a significant contribution to humanity. The author proposes a new Grand Challenge for boosting the research in this area: develop an AI system by 2050 that can make Nobel Prize-class or even greater scientific discoveries (Kitano 16). This should be most relevant for life sciences coping with massive information and struggling to understand/control complex targets, issues that AI can help overcome. The Nobel Prizes in question here are Physiology/Medicine and Chemistry. Ideally, physics should be within the scope of this challenge, but this article will focus on discussions around the author's field of expertise, life science.

First, the true target of this Grand Challenge scheme needs to be clarified. It is to understand the essence of all scientific discoveries, develop a knowledge system to support an exponential growth of our knowledge, which will lead to solving humanity's current problems. The term "Nobel Prize" is simply an attempt to present the level of scientific discoveries expected from this approach in a way that is easily understood by everyone. Winning the Prize is not the ultimate goal. To reiterate, this Grand Challenge is aimed at understanding the nature of scientific discoveries and creating a system that can autonomously make such discoveries, and, ultimately, can solving humanity's manifold problems. This is the same thinking behind the RoboCup competition. The goal of RoboCup is to develop a team of completely autonomous humanoid robots that can beat FIFA World Cup champions by 2050 (Kitano 97), but the project's true aim is to spread the technologies developed by this initiative throughout the world. On the other hand, the proposed Grand Challenge will focus on human intelligence, an area not covered by RoboCup.

### 1.1. Reconsidering scientific discoveries

Research into scientific discoveries by AI system, "machine discovery," is not new (Gil 12 and 14). Many pioneering researches exist, such as BEACON (Langley 87), DENDRAL (Lindsay 93), or AM and EURISCO (Lenat 84). These, and other existing studies, however, have been attempts at rediscovering known principles by computers, or at creating new expert systems, and have not led to major scientific discoveries in the true sense of the word.

These approaches were later taken over by researches into data mining and other methods of acquiring knowledge from a massive data collection, known as knowledge discovery from database (KDD). This newer approach has been extensively applied for analyzing individual correlations and causal relations (Kulkarni 90, Zupan 07), but it has not led to studies in autonomously discovering the underlying principles.

Today many scientific disciplines handle massive data on a daily basis, using various types of IT infrastructures with enormous computing power. The changing situation is the background for the author's belief that the time has come to revisit the idea of scientific discoveries made by AI.

### 1.2. AI and the Grand Challenge

Past Grand Challenges had played important roles in AI development. Computer chess gave birth to many search algorithms and parallel computation techniques, until the IBM Deep Blue beat Chess Grand Master in 1997 (Hsu 04).

IBM then built Watson to win against human champion in the popular quiz show Jeopardy!, which it did (Ferrucci 10). In Japan, the game of *shogi* became the Challenge battleground. The latest AI system can win against professional shogi players. There is also now a *go* system, AlphaGO, that can beat high-level *go* masters by combining deep learning and reinforcement learning (Silver 16).

One of other Challenges straddling AI and robotics is the aforementioned RoboCup, started in mid 1990s with the aim of developing a team of completely autonomous humanoid robots that can beat FIFA World Cup champions by 2050. The project has already resulted in many new technologies and spin-off businesses (Kitano 97).

These developments show that Grand Challenges with right targets and implementations can make a large difference to the evolution and propagation of AI. Previous Challenges were confined within the areas of information processing and/or closed systems. The proposed new Challenge will be an open one (Tokoro 10). Starting a Grand Challenge for making scientific discoveries can have a huge impact.

### 1.3. "Human-like AI" and "Human-transcending AI"

These Grand Challenges all aim at developing AI systems that surpass human capability. This is different from "human-like AI" perceived by the imitation game proposed by Turing (Turing 50). "Human-like AI" can be a viable field of study for understanding humanity but will not be useful for researches focusing on real-life applications. Human-like AI is interchangeable with human researchers. It should also be said that capabilities on par with human beings will not justify new investments. Furthermore, human-like AI is expected to show only the positive side of humanity. Its negative sides such as making mistakes or being insensitive/unthoughtful are out of question. It remains to be seen if those undesirable human traits can be really taken out of human-like AI. Even for the "agents" designed to support people's daily lives, "human-like" do not mean "having both the advantages and disadvantages of human beings."

The aim of this new Grand Challenge is to develop an AI system specializing in scientific discoveries and surpassing human capabilities in this field. The AI is super-human in a specific and limited area.

## 2. Life sciences' bottleneck

Life sciences have made an amazing progress. Discoveries in basic fields alone have been astonishing, as well as in applications, where many new treatments and medicines are being developed. On the other hand, researchers are burdened with huge amount of data as well as complexities of the targets they study. Especially noteworthy is the exponential growth of the amount and variety of data they handle after system biology research (Kitano 02a and 02b) became commonplace. One of the main challenges for life sciences now is the difficulty in correctly analyzing and understanding these data. Here we must take a deep breath and consider the possibility that human brains may not be the best tool for processing massive and varied data or understanding the behaviors of complex, multi-dimensional, and non-linear systems. First, we will analyze the limitation of human cognition in life sciences.

### 2.1. Information horizon

Life science experiments generate a very large collection of varied data. Papers published in this field have grown exponentially, with over one million articles coming out each year (Kendrick 14). This means that scientists can no longer read through the entire literature even if they limited their endeavor to the field of their expertise. This results in inevitable large blind spots for researchers trying to interpret as much papers and data as humanly possible. This is the “information horizon” problem.

As an example of extracting knowledge in life science labs, we shall consider mapping molecular interactions based on papers and database. In order to build a molecular interaction model, even a small one of individual systems for transducing signals concerning epidermal growth factors and the immune system, the research team must scrutinize hundreds, if not more than one thousand, of papers and a large body of database, retrieve consistent data, then redefine them in forms relevant to their research (Caron 10, Kaizu 10, Oda 05, Oda 06). This is a completely manual process (Fig. 1) (Matsuoka 15). It is not realistic to expect that creation of highly accurate maps in such a primitive way is sustainable. The result is that an accurate map, once made, is not updated (by continuously integrating new findings). Attempts have been made to improve and automate the process by applying methods used for processing natural languages, but due to inherent difficulties in processing natural languages as well as the information gap described in the next section, a practical approach has not been established yet (Kemper 10, Li 14). This is just one example of information output overwhelming human processing capacity. This is not a problem just for general studies where the information thus left out will not have a great impact, but also for medicine and other highly specific disciplines where such ignorance can be fatal.

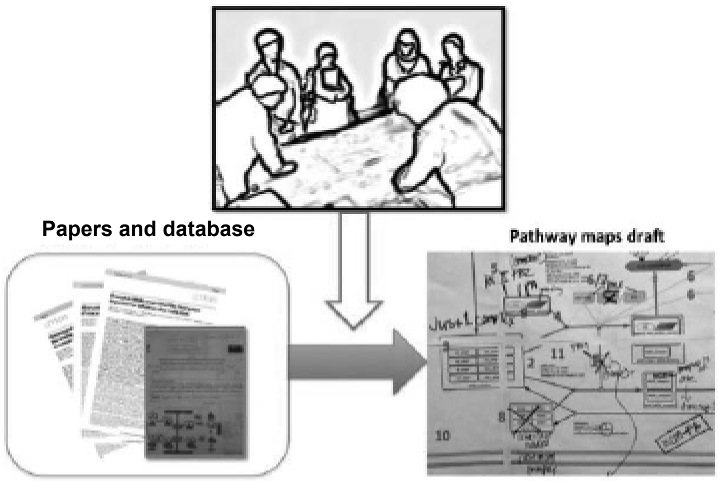


Fig. 1 Process of building a comprehensive map for molecular interactions

The process of filtering and reorganizing useful knowledge from a huge collection of papers and database is still dependent on manual labor.

### 2.2. Information gap

There is also a gap in information when trying to understand individual paper. For example, consider a researcher parsing a line saying (Shimada 00) “In contrast, in response to mating pheromones, the

Far1-Cdc24 complex is exported from the nucleus by Msn5." This intermolecular action can be presented as in the lower part of Fig. 2, using the SBGN (Le Novere 09) style which is the standard form for representing intermolecular actions in the field of system biology. Fig. 2 text describes the transition of Far1-Cdc24 complex from nucleus to cytoplasm. This is not stated in the original sentence but can be supplemented by basic knowledge of cytobiology. However, the same original sentence does not say whether any biochemically modified Cc24Far1 complex would be transferred, or if any Msn5 would also be involved in the transfer. For retrieving accurate knowledge, the researcher must find this information elsewhere. The process of text interpretation and knowledge supplementation is rife with risks of biases and misinformation. Many biology-related databases are already available. When using them not only as data storage, but as a base for extracting knowledge through human interpretation, there will always remain the possibility of biased judgements and misunderstandings. Retrieval of information is also a highly labor-intensive process which is not sustainable. When the target is images, not texts, coming from experiments the same problem of interpretation persists. These are the issues surrounding the current style of presenting biological research results, wherein papers employing natural language and images are published and shared.

This issue cannot be resolved by simply researching how texts and images in these papers can be interpreted. A more constructive approach would be to design a system focusing on knowledge acquisition while understanding the underlying cognitive process.

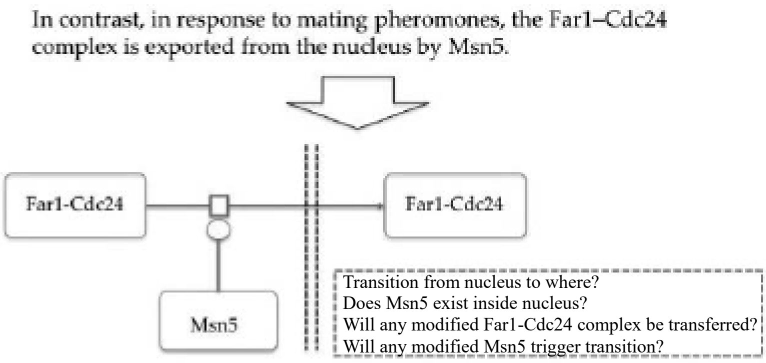


Fig. 2 Information gap (text from Shimada 00)

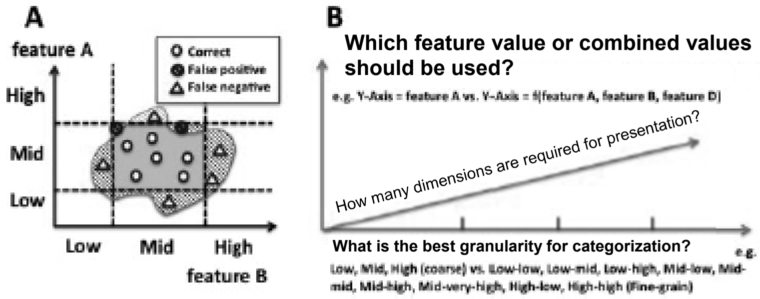


Fig. 3 The best description for a multi-dimensional non-linear target

### 2.3. Phenotype descriptions are inaccurate

Next problem is the inaccuracy of phenotype description. In biology, a phenotype is the categorization and its symbolic representation of research targets' status and phenomena. Disease types, changes in forms and behaviors after mutation, response to external stimulus, and other characteristics are categorized and labeled. The phenotypes actually used often depend on researchers' subjective decisions.

The categorization, in turn, depends on terms and concepts used. This is where the human cognitive limitations become a problem.

Biological phenomena are very non-linear. We shall consider how a non-linear target can be described. Fig. 3 shows a non-linear field. First, the researcher must determine the best unit of measurement for the horizontal and vertical scales. Typical considerations include whether generic characteristics can be directly used, or different dimensions have to be combined into a single axis. The next question to be asked is the granularity of the data, e.g. should a three-grade scale of large/medium/small be enough, or does it have to be very fine-grained. Minute scaling for an aggregated axis might enable a minute grouping of data and extremely precise analysis, but could we discern the meaning of each data? For instance, what is the meaning of data belonging to the Group 00101-00108? No matter how minute the scaling might be, so long as all data are subject to human interpretation, representations without useful meanings are unlikely to remain in use for a long time. When human beings group data based on their experience, they start by setting a limited number of categories based on significant characteristics that are easy to understand. While this style of categorization may be closely linked to the granularity of human thinking and communications, it does become a problem when precision is critical.

As a matter of fact, the imprecise clinical diagnosis based on a broad, empirical grouping of diseases has always been an issue. In the case of Marfan syndrome, a rare type of genetic disease, it took five to 30 years for the 25 percent of patients to be diagnosed, with the additional catch that in 40 percent of these cases their initial diagnoses were wrong (EURORDIS 07). For different diseases sharing the same superficial symptoms, individual patients cannot be precisely diagnosed unless a highly accurate data of disease feature values (called "biomarkers" in life sciences), their combinations and diagnosis keys are properly maintained. Next, we can consider an opposite case, where there are twenty or so diseases with slightly different causes (called disease sub-types) but are known to have mostly the same symptoms. If doctors give the same diagnosis to all of these diseases and treat them in the same way, only the patients lucky enough to be suffering from the disease sub-type that matches the treatment are likely to recover. Furthermore, under the same circumstance, if a drug is formulated based on the particular sub-type's growth mechanism and used for a group of patients having different disease sub-types but are still considered to be within the same broadly-define category, the drug's effect will be confirmed only on some of the patients, while the same drug being evaluated as non-effective for the remaining majority of the same group. In reality, for many diseases affecting the central nervous system and other body parts, disease names are used as umbrella terms for different disease sub-types having distinctive mechanisms. By introducing highly precise groupings of disease, patient cohorts can be determined with much better precision, opening the way to superior treatment strategies, the best trial plan in the drug formulation process, and even biomarker identification. Unfortunately, human experience is not enough for finding the appropriate feature values or the required data granularity.

### 2.4. Cognitive bias

Whenever we human beings use language to express, hypothesize, or communicate, we encounter a "cognitive bias." Describing biological phenomena using natural language means this bias is always to be expected.

Alfred Korzybski, a proponent of general semantics, said "map is not a territory" to explain this problem (Korzybski 33). What he meant was that there is no guarantee that different persons observing the same phenomenon will always show the same understanding or describe it in the same words. This problem is related to the issue of unprecise description discussed in the previous section. Unless the categories used in the description are determined quantitatively, that description will always be subject to variances caused by human and therefore subjective decisions. Such outcomes are inevitable in any system involving human beings. Systems designed to eliminate human intervention as much as possible might be the solution to this problem.

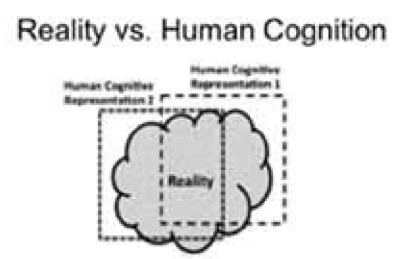


Fig. 4 Cognitive bias is inevitable

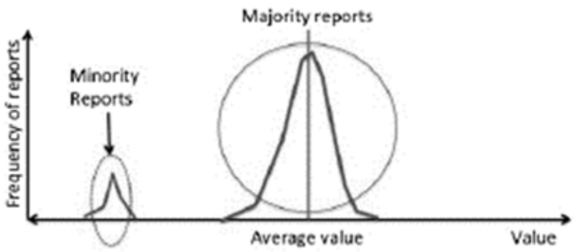


Fig. 5 Minority report problem

### 2.5. Minority report

When only three out of 1,000 papers have different conclusion from the other 997, are these three just wrong, or are they different but legitimate outcomes under special circumstances that should be treated as new discoveries? This is one example of the minority report question. To begin with, reading through 1,000 papers is a difficult enough task for human brains. Being able to go further to find contradicting reports in a very small number of those papers and ponder upon them is quite rare. Still, it is always possible that those outliers are not incorrect but important discoveries. The key is to treat life science data with the assumption that a certain amount of errors, test issues, or even forgery will be included (Alberts 14, Prinz 11). Once the three minority reports are cleared of these doubts, they are very likely to lead to new discoveries. Still, they are part of a large volume of reports that are not always reliable. Deciding their worth can be extremely difficult.

We have discussed the difficulties faced by life science researchers because of human cognitive limitations through information horizon and minority report examples. Another issue is that various hypothesis required for advancing researches are seldom formulated in a comprehensive and systematic style. In many cases these hypotheses are merely based on the researchers' intuitions or logical thinking within a very limited scope. Until the root cause of these problems is solved, the process of scientific discovery will remain at the level before the days of industrial revolution.

## 3. Building an engine for scientific discovery

So far, we have discussed the barriers created by human cognitive limitations in life sciences. Life science is knowledge-intensive in many ways. Researches in this field will be meaningless unless they are based on a very large volume of knowledge. In that sense, it is important to overcome this problem with an AI system.

Still, that alone is not enough for scientific discoveries. New knowledges must be sought by consolidating existing knowledge before identifying targets. The steps to this type of scientific discoveries, though, has mostly been not understood. While much discussions have been made, including the arguments made by Popper (Popper 59) and Kuhn (Kuhn 62), and the general importance of “scientific intuitions” and “serendipities” have been pointed out, practical steps for implementing those ideas have remained unclear. In other words, there is virtually no methodology for automation nor engineering support available for this process. Technologies for comprehensive and precise observation as well as for simulation and numerical analysis have evolved, but the “discovery” part still depends on individual intuitions and serendipities in a style highly reminiscent of cottage industries. In that sense, the scientific discoveries are still made in mostly the same way as in days before the industrial revolution. Radical changes for industrialization must be started in this area.

### 3.1 The essence of scientific discovery

The remaining question is to how the process of scientific discoveries can be automated. This is a very difficult problem but not without hints. The key process of any scientific discovery is “formulating and challenging a hypothesis.” This is based on the basic concept of falsefiability (Popper 59) and is fundamental to all scientific processes. Kuhn also said that when a prevailing scientific paradigm shifts, two incompatible theories (or interpretation frameworks) will clash (this is called “incommensurability”). The shift will then trigger a wide range of re-interpretations based on the new dominant theory (Kuhn 62). Implementing a new computational theory will be another challenge at this stage. There are many other philosophical and/or psychological studies on scientific discoveries and human creativity (Feyerabend 88, Hanson 58, Weisberg 86). Adopting them all would not be a good idea, but workable findings should be incorporated. At the same time, discussion on scientific discoveries and scientific philosophy need to be evaluated while keeping in mind the developments since Kuhn and Popper as well as the possibility for their implementation as part of computational theory.

The hypothesis behind the proposed Grand Challenge is that scientific discoveries made through a comprehensive search and evaluation of a hypothesis space. The idea is that formulating hypothesis quickly and comprehensively, then evaluating them, would lead to a string of discoveries. This is a brute-force approach. This is an approach different from the human process for scientific discoveries that may still lead to other types of scientific discoveries.

A likely question for this approach would be: can computers make discoveries based on coincidence or errors, which have been the source of many scientific findings? One can answer this question by saying that discovering a new knowledge by coincidence or mistake means that the answer came from a hypothesis space outside the normally expected area. An additional explanation would be that the parameters of the experiment in question was far outside the designed range, accidentally setting up an environment that was both unexpected and acceptable for a new discovery. The logical conclusion of this idea is that the same result can be derived by searching through a very large parameter space.

Another challenge to the proposed approach may be: can computers have scientific intuitions and ask the right questions, the two critical components of human scientific discoveries? If this is a legitimate doubt, then the new AI system must incorporate those two functions.

Asking the right question becomes important when a researcher desires to make a discovery in a limited amount of time to build a successful career or any other reasons. In that case, instead of evaluating all the possibilities, the researcher must “ask the right question,” formulate a hypothesis accordingly, then evaluate it through experiments. So long as this process is completed in a highly efficient manner, asking the right question becomes not so critical. This is because “asking all the questions” and examining all the hypothesis should guarantee that the “right question” is included. The next agenda, then, would be how many valid hypotheses can be generated and how efficient the process of validating and challenging them can be.

The "scientific question" asked by this Grand Challenge is: what is the essence of scientific discoveries? Starting from a hypothetic answer to this question, the Challenge can build a new style of scientific discoveries different from that of us human beings.

**3.2 What the Grand Challenge can teach us**

This approach may seem like a brute-force effort. Here we must look back at the history of AI Grand Challenges. Many things can be learned from it. In case of computer chess, the brute-force approach initially had hit limitations. It was thought that the heuristics behind human intelligent activities had to be understood and implemented to the computer. *Computers and Thought*, published 1963, says in Page 6:

"Brute-force computing through problem mazes (for any but the most trivial problems) just won't do. Problem-solving by this method is beyond the realm of practical possibility." (Feigenbaum 63)

What actually happened was exactly the opposite. The computer chess finally beat a Grand Master by analyzing a huge database of past matches by massive computation to develop the best algorithm for evaluating the pieces on board and simulating their future movements (Hsu 04). The *shogi* computer followed the same route. Newest *go* computer systems are also built around their ability to learn from massive databases (Silver 16).

The same change took place in the field of voice recognition. Here researches on spectrum reading expert systems specifically designed for analyzing voice signals were once dominant (Zue 86). However, a different approach for building model frameworks based on the Hidden Markov Model to use massive database for machine learning through massive computation proved to be far more practical for boosting the voice recognition level (Lee 89). The major contributing factors were massive database, massive computing, machine learning, and the appropriate model. Computer *shogi* is mostly built on computer chess, but new methods have been adopted as well, e.g. deciding the next move based on consensus between multiple algorithms.

IBM's Jeopardy! Project shows how key components had developed. Open data access, distributed real-time inference, heterogenous learning strategy are all vital. The fact that the Jeopardy! was an open-ended question project made it an interesting research subject. The only framework was that the program was a quiz show. Anything might be asked. The traditional approach for handling this case would have been to build a large knowledge database like CYC (Lenat 90) over a long period of time. The fact that the Project succeeding in surpassing human champion using an approach based on open data access becomes significant. The availability of massive database and massive computing are also critical for the deep learning technology gaining much attention now (Bengio 09 and 13, Hinton 11). Massive data, massive computing, machine learning in a broad sense have become the base component, with its development accelerating between each Challenge (Fig. 6).

The "massive AI" and "super-parallel" predicted by the author (Kitano 93 and 94) have been realized in this development, clearly demonstrating that difference in quantity is turned into difference in quality.

At the same time, it should be noted that the AI methodologies employed by these Challenges are not the same with the intellectual processes applied by human minds to the same types of questions. The proposed Challenge will be no different. The process of scientific discoveries established once the Grand Challenge has been successfully completed may be different from the traditional human approach.

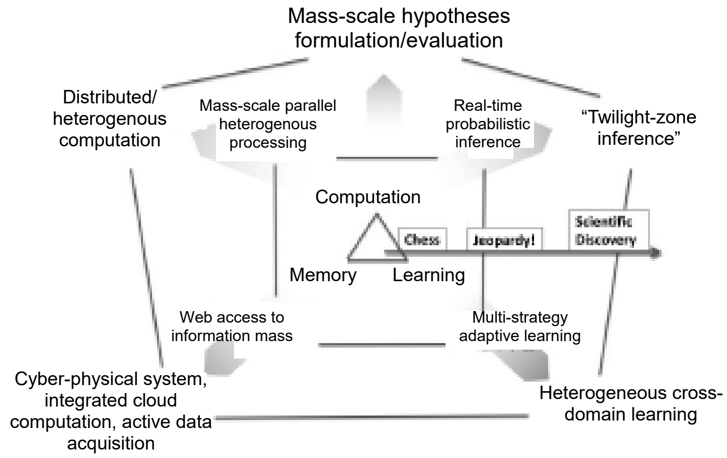


Fig. 6 Transition of component technologies in Grand Challenges and technologies expected to play critical roles in scientific discoveries

## 4. Implementation strategy

We can now consider what kind of system should be built based on the discussions so far. This system will be built from many modules having different features. Each of these modules must keep evolving together with databases they use. This means that the new system architecture will be built on a flexible but stable platform based on open API. For some years the author's group has been developing Garuda Platform, a platform for promoting open innovation in the field of life science which has been adopted mainly by pharmaceutical businesses inside and outside Japan (Ghosh 11). The Challenge project will also use this Platform.

The core engine and the function module set built on this platform are even more important. The core engine design must be based on the hypothesis for scientific discoveries already discussed. Each of the function modules must have a structure that can always be pushed to its limit for maximum generation and evaluation of hypothesis. The basic cycle, as shown in Fig. 7, would begin with mass generation of hypothesis, passed on to the challenge/validation engine for evaluating their reliabilities.

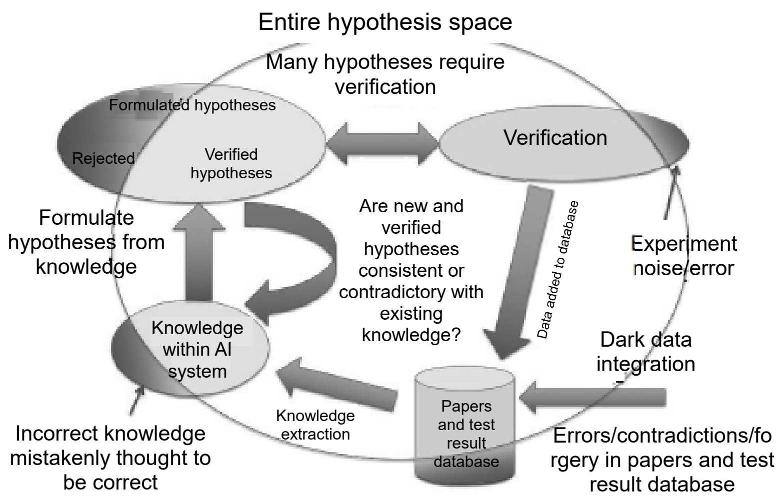


Fig. 7 The process of verifying/challenging hypotheses must be linked with various function modules

### 4.1 Core engine: The engine for massive generation of hypotheses and the disproof/verification

The realization of massive generation of hypotheses and the disproof/verification cycle at ultrahigh-speed and high accuracy is the basic concept of this project. The most important and undeveloped area is the generation of hypotheses. The hypotheses which are not generated in this stage can't be disproved or verified. Therefore, all hypotheses including those which seem to be preposterous need to be generated. However, if hypotheses are generated totally at random, it is too inefficient and unpractical. So, we need to set a certain restrictive condition for generating hypotheses, but we need to be extremely careful about the decision of the condition, because, this decision is the answer to the question which sets a boundary between possibilities and impossibilities, in other words, "what are things which can't happen in this world?" Meanwhile, the significant scientific discovery does not come to mind suddenly without any basis for the discovery. The hypotheses are generated on the basis of the huge accumulation of knowledge. Thus, what is important here is to "generate all possible hypotheses and send them to the disproof/verification process" without undergeneration at the stage of generating hypotheses.

Furthermore, in the disproof/verification module, a series of processes (e.g. consistency with the data and existing knowledge, experimental verification, etc.) start to evaluate the credibility of each hypothesis. If the hypothesis shows high credibility, the hypothesis is regarded as verified, and turns to knowledge, and its data are added to the knowledge database. In this process, regarding a statement, we call it "hypothesis" before the verification, and if it shows high credibility through the verification, we call it "knowledge." However, after careful consideration, the boundary between "hypothesis" and "knowledge" is not so clear. In the empirical sciences, the verification means that "there is a strong possibility that a hypothesis is true, because it has survived through a series of disproof process for the moment." This ultimately means, the verification process of all hypotheses and knowledge needs to be recorded. On the other hand, all disproof/verification process regarding the rejected hypotheses is recorded and stored. If any significant change happens in the course of such process, automatic restart of reexamination of applicable hypotheses is required.

Single information which is just extracted from theses and databases is not meaningful knowledge. We need to place it with consistency in the mechanism where a certain interpretation is possible. In the case of life science, the mechanism needs to be along with the purpose of understanding of life system and disease mechanism. It means that fragments of knowledge which is extracted from the information source should be available for the use for understanding the mechanism of life system and estimation of actions, and even understanding the unknown phenomena. The method which enables explanation of actions and forecast by utilizing knowledge (e.g. qualitative reasoning) should be required as one of mechanisms [Forbus 11, Iwasaki 97]. Also, it is possible to generate a series of hypotheses from this process. Now, let me refer to Truth Maintenance System of knowledge and hypotheses which is a counterpart of qualitative reasoning to some extent [Doyle 79]. In this area, a series of methods were developed, such as, Assumption-based Truth Maintenance System (ATMS) [de Kleer 86], and Justification-based Truth Maintenance System (JTMS) [Forbus 93]. Such methods are used for estimation of the status of the object, by generating all combinations of possible statements which satisfy the restriction under the certain condition. ATMS was supposed to be applied to fault diagnosis of complex machines, and generation of hypotheses regarding the status of machines. If we regard an animate being as a molecular machine, such method can be theoretically applied. In such case, regarding how to correspond to the status to the node which consists of the Lattice of TMS, we need to reexamine by reflecting the performance of Deep Learning and the latest knowledge representation. The same should be applied to the qualitative reasoning. When we reintroduce methods of classic AI, we need to verify the limitation and possibility of such methods at the present time.

The great challenge in the part of generating hypotheses is regarding how to give the seeds for generating hypotheses, or, whether the system becomes able to autonomously and effectively search the hypotheses generating area itself from a certain degree of stage or not. This is difficult but fundamental challenge which relates to the essence of scientific discovery.

**4.2 Knowledge-intensive modules**

The knowledge-intensive modules are immediately linked together to generating hypotheses and the disproof/verification process. The major role of these modules is consolidation of knowledge which is the base of generating hypotheses, and the maintenance of consistency.

Since life science is the deductive and knowledge-intensive science, the consolidation of systematic knowledge is the base of significant scientific discovery. However, the edifice of knowledge is dispersed among theses and respective databases, so the knowledge has not been accumulated systematically in computable forms. Though the research of knowledge extraction from theses are conducted in the field of BioNLP, the focus of research is currently placed on the aspect of understanding language [Li 14]. In future, the approach should be shifted to the aspect of knowledge extraction and accumulation. In America, DARPA Big Mechanism Project has started, and development of technology for on demand extraction of knowledge regarding molecular interactions from massive theses is in progress [Cohen 14]. Also, IBM Watson has started the application to the medical science area, and has established the system to support diagnosis and a part of process of development of new drugs, on the basis of contents of massive theses in the cancer area [Ferrucci 13, Spangler 14]. However, no system has yet reached the stage where massive knowledge of medical care and complex life phenomena is systematically and dynamically accumulated. Besides, analysis and knowledge extraction regarding images data in theses and databases have not started yet, so they will be significant themes to be pursued. Actually, adequate extraction and systematic accumulation of knowledge can't be possible without understanding both parts, namely, the part written in a natural language, and the part of images listed. Furthermore, we usually understand contents of theses, etc. by compensating insufficient information, with the access to wide variety of information resources other than theses, in the course of understanding them. Therefore, "active search skill" which is ability to not only analyze the natural language and images in theses but also actively search for information is required. In active vision research, which is the research of computer vision, the camera is moved actively to get lacked information [Aloimonos 88, Ballard 91]. This is a similar case.

Moreover, there are huge reports of experimental results in theses and databases. When we intend to forecast experimental results under a certain condition, currently we tend to check results of statistical analysis, or conduct simulation. However, as a result of massive data consolidation in future, the forecast of experimental results will be possible by utilizing the past experimental data themselves. Namely, the already reported fact will be used as the model of the actual world. While Brooks used the physical world itself as the model of the world, in "Intelligence without representation" or "Intelligence without reason" [Brooks 91a, Brooks 91b], we can apply this way of thinking to the more complex context of life science, and consider the use of theses and databases as the model of the world, as "Simulation without computing."

Besides, contents of theses are not necessarily always correct. There are experimental errors, noises, and even fabricated theses. It is also a problem that many of experiments mentioned in medical chemistry theses can't be reproduced [Alberts 14, Prinz 11]. It is not easy to judge whether the knowledge extracted from such theses has consistency with the other edifice of knowledge or not, and if the extracted knowledge is inconsistent with other edifice of knowledge, we have to face the difficult judgement to identify the cause of contradiction (e.g. errors, fabrication, or new discovery). The aforementioned Truth Maintenance System (TMS) can be partially applied. However, in the conventional grand challenges, the given information was supposed to be basically true. If there was a noise in the sensor value at the time of robotics challenge, the wrong data were not intentionally given. However, in the real world, there is intentionally fabricated information. The information processing in this extremely delicate and mysterious area is called “twilight-zone reasoning.” It is the great AI challenge regarding how to evaluate information in this area and appropriately process it.

Thus, we need the function to systematically extract knowledge in the life science area and continue to expand in a consistent manner.

### 4.3 Data science modules

Today’s life science also has the aspect of data science. Huge data (e.g. genome sequence, genetic expression, metabolome, live cell imaging, etc.) are generated every day. It is extremely important to discover a determinate law in such data. Currently, this operation is basically conducted by human beings by utilizing various tools of data mining and bioinformatics. However, many of such analysis operations are no more than “feature engineering” which is the term in the artificial intelligence area and means the analysis of which feature or feature combinations to be used, on the basis of the conventional and empirical knowledge. Also, currently, researchers judge what kind of analysis should be conducted. Consequently, even if the data have the potential of new discovery, researchers can’t find it without appropriate judgment. So, there is plenty of room for improvement by development of methods by utilizing the active search skill and a series of machine learning including Deep Learning, etc.

The role of modules handling such massive data is extremely extensive and important. For example, presumption of correlation and a relation of cause and effect from massive data at high accuracy to lead to a trigger of generating hypotheses. In case of presumption of credibility of hypotheses in the verification process, massive data are also utilized. For instance, the algorithm which comprehensively presumes molecular interactions and control relation between genes from massive data of genetic expression and mass spectrometry data is currently and actively developed [Hase 13, Marbach 12, Meyer 14]. Also, the research of method to presume candidates of disease biomarker from clinical data and experimental data of cultured cells is in progress [Bansal 14, Costello 14]. This area is the core research area of life science, and stable opportunities for resources and evaluation are offered by the initiative of DREAM Challenges, so the development of various analytical methods will be accelerated in future. Thus, it is important that such methods to be developed can be used as a part of the system which we discussed in this thesis. Furthermore, we need to consider how such methods are linked together to the core module to fully utilize such function for generating hypothesis and verification.

### 4.4 Experimental modules which utilize robots

So far, we have mainly discussed on data and knowledge space, but since life science is experimental science, experiments are essential for actual life science. Experiments are necessary for extremely wide variety of purposes (e.g. verification of highly credible hypotheses, complementing the lacked data, reconfirmation of basic experiments, etc.). Firstly, establishment of automated experiments is premised on such stage of experiments. Making appropriate experiments plans, confirmation of protocols, ensuring reagents, etc. are required for implementation of actual experiments for various purposes, such as, verification of hypotheses, and complementing the data, etc.

Then, utilization of robots brings great advantage for experiments. Firstly, the huge number of experiments is required for this system. Secondly, the experimental methods greatly vary, so the large-scale robot experimental facilities are necessary to conduct such experiments promptly and accurately.

Thirdly, the accuracy of experiments is improved. As Natsume group of National Institute of Advanced Industrial Science and Technology (AIST) already clarified, the introduction of robots drastically improved the accuracy of experiments. Such improvement mitigates fluctuation and noises in experiments, and it will lead to more precise measurement of actions of biomolecule which we haven't noticed so far.

Regarding the integrated system from generating hypotheses to automation of experiments, we can refer to Robot Scientist system developed by Ross King (the University of Manchester) and other members [King 04, King 09a, King 09b]. This system succeeded in automation at the initial stage of scientific discovery, by generating simple hypotheses in the area of genetics of budding yeast and verifying such hypotheses by utilization of automated experiments device. However, the focus of automation is basically placed on dispensing robots, etc., so it is not the case of utilization of authentic manipulator to improve accuracy, like the case of AIST.

In this challenge, we need to automate all processes from generating hypotheses to verification, so, all experimental apparatuses need to be connected, controlled, and linked together to data. Also, the automation of all experimental processes including robots enables automatic accumulation of total data which are generated in such processes, in an appropriate manner. This can solve the so-called dark data issue [Heidorn 08], and furthermore, lead to the fundamental solution to the fabrication issue, by the combination use with BlockChain, etc.

Since this area is the fusional area of robotics, data science, artificial intelligence, so many applications can be generated at the remarkably early stage.

## 5. Continuous development in the actual world

So far, we have discussed the project of "development of AI system that can make major scientific discoveries that is worthy of a Nobel Prize in the life science area by 2050," but we also expect that spin-outs which have significant impact can be generated in the middle stage of the research, like the case of other grand challenges, such as RoboCup, etc. For example, Raff D'andrea (Cornell University) who participated in the minor league of RoboCup developed a system where plural autonomous robots can be in charge of carrying goods in a warehouse, by application of the technology which had been cultivated by RoboCup. Then he established a company, KIVA Systems, and the company was acquired by Amazon.com for approximately 80 billion yen. The company is currently called Amazon Robotics.

Also, a participant team of RoboCupRescue was later in charge of search operation at the site of the World Trade Center attacked by terrorists, and demonstrated its remarkably effective operation. Besides, some of robots which are currently in charge of search operation to check the status inside nuclear reactors at the disaster site of Fukushima No. 1 nuclear power plant are based on robots of the team of Chiba Institute of Technology (CIT) which participated in RoboCupRescue.

Also, in DARPA Grand Challenge which had been derived from RoboCup in some sense, themes relating to self-driving vehicles and humanoid were set, and the Grand Challenge contributed to technological development especially in the area of self-driving. So, we expect that the challenge in this project will bring the similar impact.

### 5.1 Support system for the research of life science and medical chemistry

It almost seems needless to say that a series of modules and experimental system can be immediately used for usual support for the research of life science. In many of conventional grand challenges, other themes which are different from industrial issues (e.g. soccer, chess, etc.) are set, and the results are applied to issues. However, in this challenge, the life science research which is the impactful issue itself is the grand challenge. Therefore, this project has a feature that the development of this research itself can contribute to the development of the area of life science.

In this case, researchers can utilize the system of this project in various ways, such as, the use for verification of researchers' hypotheses, the use for researchers' search for possible hypotheses by utilizing the hypotheses generating part of this system, etc. Such ways show that this system is truly the cooperative system between artificial intelligence and human beings, in other words, the advanced intelligence. Besides, if human beings proceed the research through communication with the artificial intelligence system, such AI system is required to have explanation capability to explain grounds for applicable hypotheses.

Furthermore, such platform will enable many people to participate in the research dispersively on the basis of the platform, which means the so-called cloud research, and participatory research. Such type of research has demonstrated its performance in presumption of protein structure, massive interaction model, verification of effect of treatment, identification of correlation between genotype and physical constitution. So, its applicability is expected [Hu 15, Khatib 11, Kitano 11, Wicks 11]. This challenge shows the interesting possibility to expand Artificial Intelligence into Population Crowd Intelligence. It is also interesting to wonder which one will made bigger contribution to the development of the system, between Artificial Intelligence and Population Crowd Intelligence.

### 5.2 Deep clinical phenotyping

Deep clinical phenotyping is one of examples of impactful applications which are expected in medical science at considerably early stage. The deep clinical phenotyping aims to establish detailed diseases phenotype on the basis of massive medical care information, omics data, lifestyle monitoring, statement data of medical expenses from patient samples, and classify patient groups accordingly [Frey 14, Robinson 12]. Many "diseases" are aggregates of various diseases subtypes in most cases. So, the symptom of each disease subtype has something in common with other subtype at a certain level, but each subtype is different from other subtype in its occurrence mechanism on the molecular level. However, such different subtypes are often classified into the same category together. Also, the aforementioned difference may be reflected on the quantitative difference of symptom. However, the accurate and precise classification has not been achieved yet, because it requires the continuous and quantitative monitoring, and extremely supersensitive measurement.

To realize such classification, we need to build the platform where multiple technology composed of IoT, Big Data, machine learning, etc. is applied and processed comprehensively. Fortunately, Garuda platform already satisfied this condition, so we can concentrate on the analytical part to be configured on the platform. For example, Deep Learning is supposed to be implemented on the platform [Che 15], but we also need to show the evidence of the classification, so just high precision is not the adequate feature to be installed on the platform. IBM Watson realized the system which enables the explanation based on public knowledge, and the diagnosis assistant, on the basis of massive thesis information, but such system does not support for new classification of subtypes. Therefore, the technology which simultaneously achieves both targets which are the extremely high precision of classification and the generation of explanatory logic of results has not been realized yet. Thus, we can see the necessity of new basic research and prompt development for application.

Of course, wide variety of examples of applications other than the aforementioned example are supposed in the initial and middle stage. Substantial time and effort are required to achieve the final target of grand challenge. Therefore, continuous demonstration of performance and results at the middle stage is especially important to continue the grand challenge.

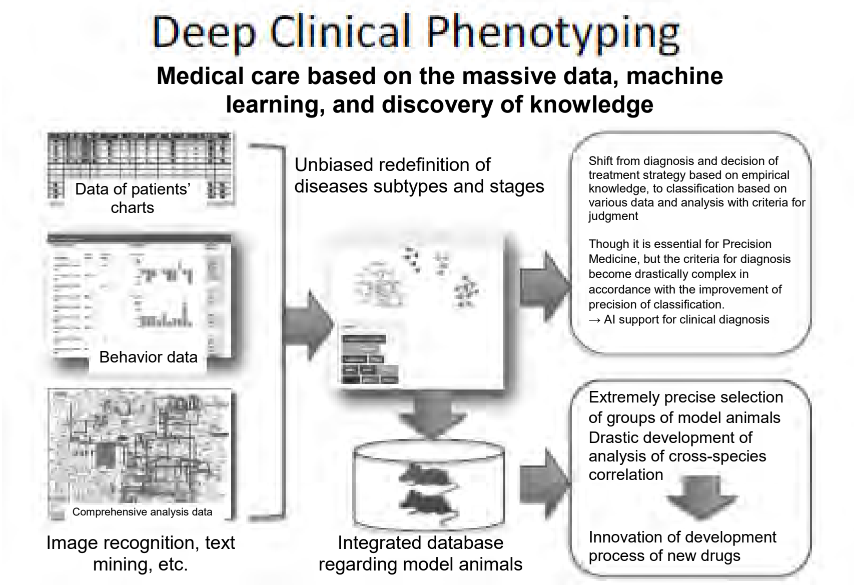


Figure 8: Concept of Deep Clinical Phenotyping

**6. New stage for human evolution**

I found that this grand challenge is qualitatively different from the conventional grand challenges so far. The conventional grand challenges seek discovery regarding how to make computers solve questions and how to make computers learn to solve questions, in various areas, such as, chess, shogi, go, quiz, soccer, etc. However, scientific discovery is actually metalevel challenge. What we seek in this time challenge is the ultimate system which autonomously acquires knowledge and continues to make discoveries, and there is a possibility that such system will evolve by itself beyond our control. This is the fundamental difference from the conventional challenges so far.

The history of evolution of human civilization is the history of evolution of tools. Main tools which human beings have utilized so far are as follows: “stone tools” as simple enhancement of function of hands, “method of farming (e.g. rotation of crops, enclosure, etc.)” as a series of conceptional tools which brought the Agricultural Revolution (later, specific tools (e.g. chemical fertilizer and agricultural chemicals) were further added), “steam engine” which supplied power, and brought the Industrial Revolution, and furthermore, “computer and telecommunications system” which enabled calculation and records to operate information, and brought the Information Revolution, etc. Such tools have had a significant impact on the state of human civilization. Meanwhile, the grand challenge proposed this time will bring a tool to generate knowledge, and this tool will decisively accelerate evolution of human civilization, and lead to explosive increase of knowledge. So, this is the development of machine which discovers issues to be solved by itself, and actually continues to solve. In other words, the machine autonomously makes scientific discoveries, accumulates knowledge, and continues to understand the world at the speed which is beyond that of human beings.

Of course, only by the methods discussed here, we can reach only a part of scientific discoveries to be made. However, if at least the functions discussed here are realized, many discoveries will be brought, consequently, life science will fundamentally launch into the next dimension. Actually, the progress of this research will bring discoveries which benefit human beings, such as, the methods of treatment for many diseases. Meanwhile, the discovery regarding technology to realize sustainable growth in the global environment may be brought. Then, we will specifically verify kinds of discoveries which can't be made by this system, and thus we will be able to explore the essence. Consequently, it will lead to generation of the system which autonomously continues to discover principles of this world, which has the possibility to fundamentally change the state of civilization.

Therefore, this grand challenge is the most important scientific research project imaginable.

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Supplementary material from Mr. Kitano




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2011: President and CEO, Sony Computer Science Laboratories, Inc.

1998 Oct - 2003 Sept: Project Director, ERATO Kitano Symbiotic Systems Project, Japan Science and Technology Corporation

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2001 April - present: President (and founder), The Systems Biology Institute

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Computers and Thought Award in 1993
Ars Electronica Special Award in 2000
Nature Award for Creative Mentoring in Science (Mid Carrier) in 2009
Invited artist for Biennale di Venezia 2000, and Worksphere Exhibition at Museum of Modern Art, New York.